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MISCELLANEOUS PAPER HL 88-5

AIR DEMAND AND CONDUIT PRESSURES STILLHOUSE HOLLOW DAM LAMPASAS RIVER, TEXAS

by

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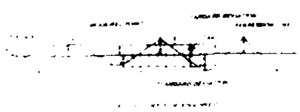

August 1988
Final Report

HYDRAULICS LABORATORY

Prepared for US Army Engineer District, Fort Worth
Fort Worth, Texas 76102-0300

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper HL-88-5	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Hydraulics Laboratory 6b. OFFICE SYMBOL (If applicable) CEWES-HS-H	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAED, Fort Worth 8b. OFFICE SYMBOL (If applicable) CESWF-ED-HD	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) PO Box 17300 Fort Worth, TX 76102-0300	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Air Demand and Conduit Pressures, Stillhouse Hollow Dam, Lampasas River, Texas

12. PERSONAL AUTHOR(S)
Hart, E. Dale

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ______ TO ______	August 1988	32

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Air demand	Sensors
			Pressure	Wall roughness

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Tests were conducted to provide data on prototype conduit air demand during high water discharges and to determine conduit losses at high Reynolds numbers (10^7). The latter information was used to compute the conduit roughness coefficient f.

Recorded data included water discharge, individual vent air demand, pressures at the air vent-water conduit interface, and conduit piezometric pressures.

A value for the roughness coefficient was determined from the conduit head loss data and compared to values determined from plaster casts of the conduit wall. Some air vent velocities were found to exceed the recommended value given in Engineer Manual 1110-2-1602, "Hydraulic Design of Reservoir Outlet Works." However, no damage was noted in the conduit at the time of the tests. Periodic inspections of the conduit were recommended, especially following extended releases.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

PREFACE

The prototype investigation described herein was conducted during June and July 1987 by the US Army Engineer Waterway Experiment Station (WES) under the sponsorship of the US Army Engineer District, Fort Worth.

The overall test program was conducted under the general supervision of Messrs. F. A. Herrmann, Jr., Chief of the Hydraulics Laboratory, and G. A. Pickering, Chief of the Hydraulic Structures Division. Mr. E. D. Hart, Hydraulic Analysis Branch, was the test coordinator. This report was prepared by Mr. Hart under the supervision of Mr. B. J. Brown, Chief of the Hydraulic Analysis Branch. Testing and data reduction assistance were provided by Mr. J. E. Hall of the Hydraulic Analysis Branch. Instrumentation support was provided by Mr. S. W. Guy under the supervision of Mr. L. M. Duke, Chief of the Operations Branch, Instrumentation Services Division, WES. This report was edited by Mrs. M. C. Gay, Information Technology Laboratory, WES.

Acknowledgment is made to Mr. G. O. Carefoot and Ms. K. M. Johnson of the Fort Worth District for their assistance in the investigation.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
square miles	2.589998	square kilometres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

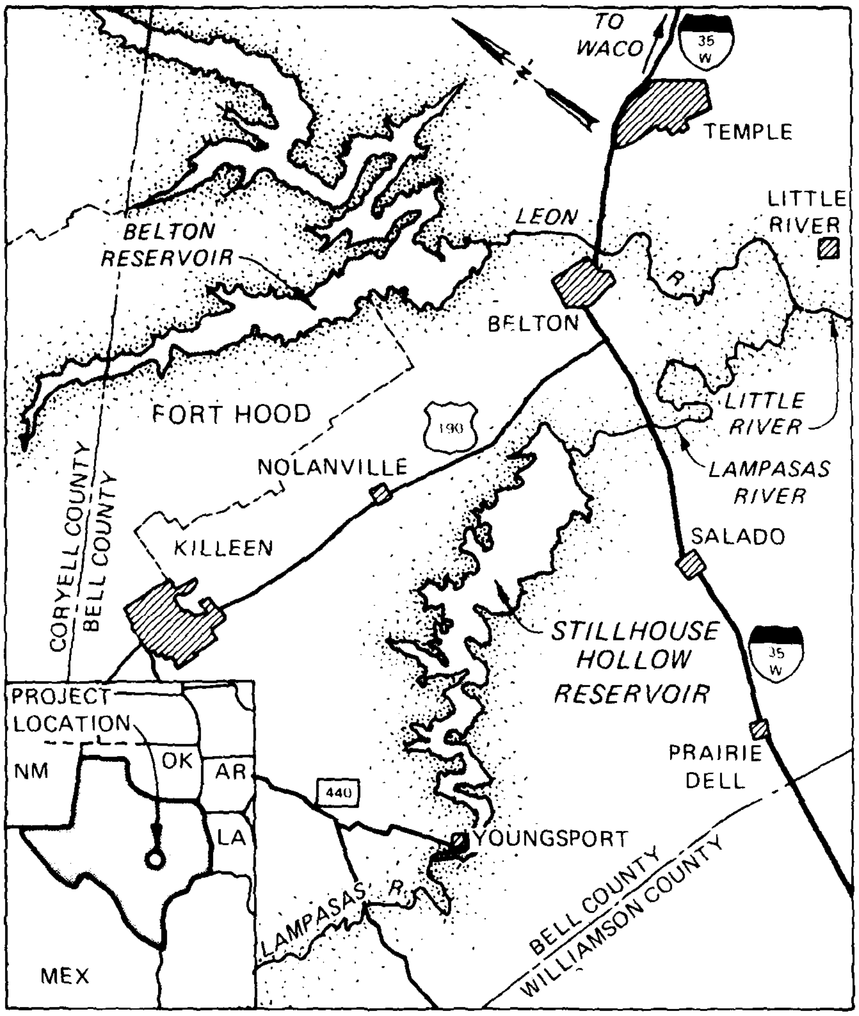

Figure 1. Location and vicinity map

AIR DEMAND AND CONDUIT PRESSURES, STILLHOUSE HOLLOW DAM, LAMPASAS RIVER, TEXAS

PART I: INTRODUCTION

The Project

1. Stillhouse Hollow Dam is located at river mile 16.0 on the Lampasas River about 5 miles* southwest of Belton, TX (Figure 1). The project and reservoir are located entirely within Bell County. Primary purposes of the project are flood control and water conservation.

2. The major embankment of the rolled earth-fill dam is 7,850 ft long. The top of the dam is at el 698.0**, rising 200 ft above the streambed. The project controls flow from a drainage area of 1,319 square miles. The dam impounds 1,013,300 acre-ft of water in the reservoir at maximum design pool (el 693.2).

3. Flow through the structure (Figure 2) is controlled using a 12-ft-diam conduit controlled by two 5-ft 8-in. by 12-ft vertical slide gates. The invert elevation at the gates is at el 515.0 and at the portal el 512.0. Maximum outflow at reservoir level el 691.0 is 8,000 cfs. An uncontrolled, broad-crested weir-type spillway is located south of the dam. The spillway crest is at el 666.0.

Purposes of Tests

4. Because of the potential high head at the project (approximately 180 ft at maximum pool) it was possible to conduct tests at a flow Reynolds number of 10^7. Such information is of value for evaluating air demand during high water discharges and determining conduit losses at the high Reynolds numbers. Also, another purpose of the tests was to compare conduit wall

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* A table of factors for converting non-SI units of measurements to SI (metric) units is found on page 3.

** All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

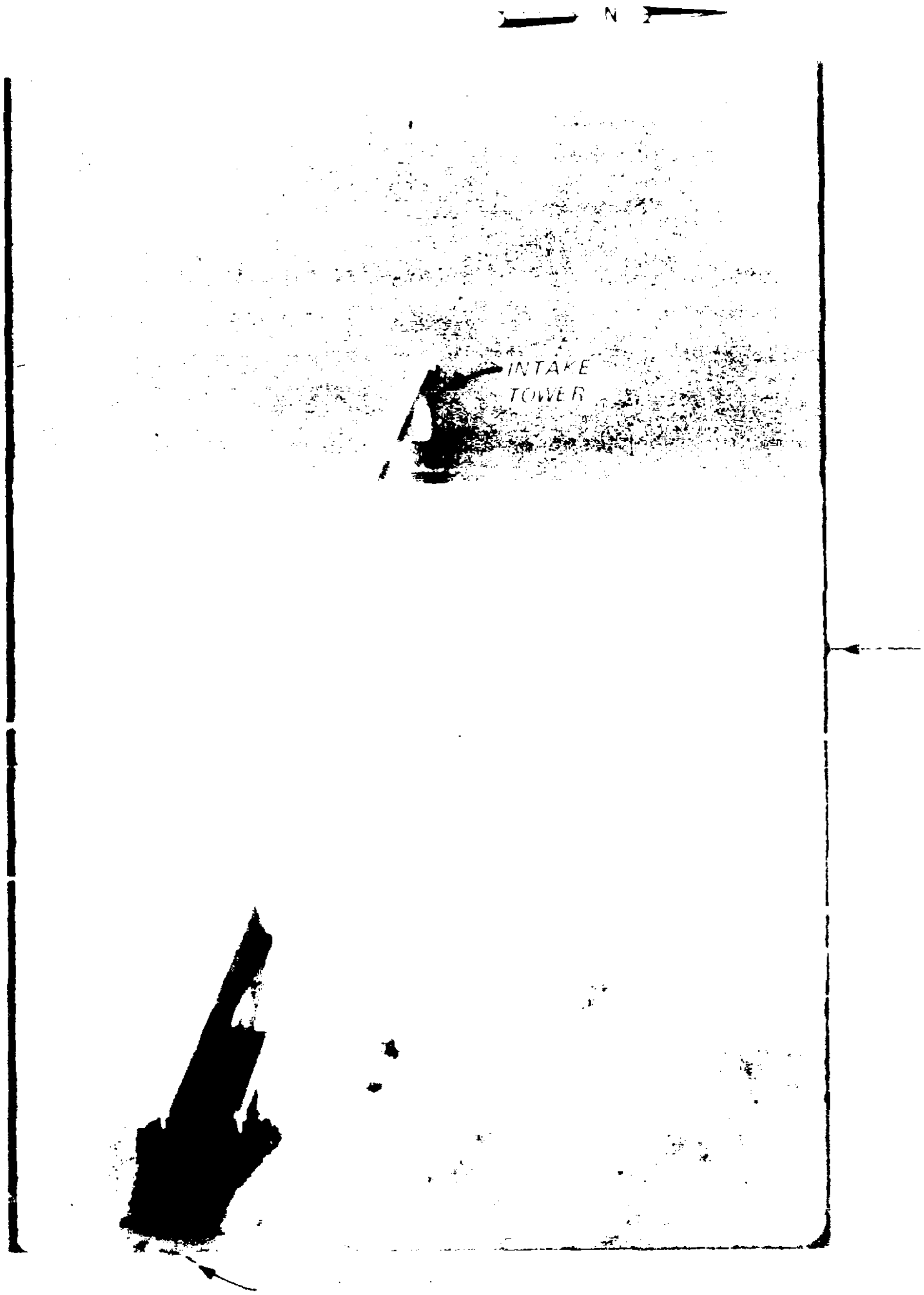


Figure 2. Stillhouse Hollow Dam

roughness values determined from plaster cast measurements and values computed using data from hydraulic measurements.

Scope of Tests

5. Five series of tests (Tests 3 and 4 were duplicates), performed under different flow conditions, were conducted at Stillhouse Hollow Dam on 30 June and 1 July 1987. The tests were run with both gates at equal openings of 4.1, 5.4, 6.7, and 8.0 ft, respectively. The pool elevation varied only slightly during the period of the tests (Table 1). The conduit flowed full during all tests.

6. Water was stored in the Stillhouse Hollow Reservoir during a period of heavy rainfall in the spring and summer of 1987. The test program was arranged to coincide with the subsequent period of flow release. Though the pool elevation did not reach the upper limit, it was determined that the data that could be obtained would be of considerable value to the US Army Corps of Engineers for design criteria refinement. In addition, plaster casts of the conduit walls had previously been taken for determining the wall roughness coefficient. It was desired to compare these with values computed using data from hydraulic measurements.

PART II: TEST FACILITIES AND PROCEDURES

Test Facilities

7. Table 1 lists the test conditions and Table 2 lists the instrumentation for the Stillhouse Hollow Dam test program.

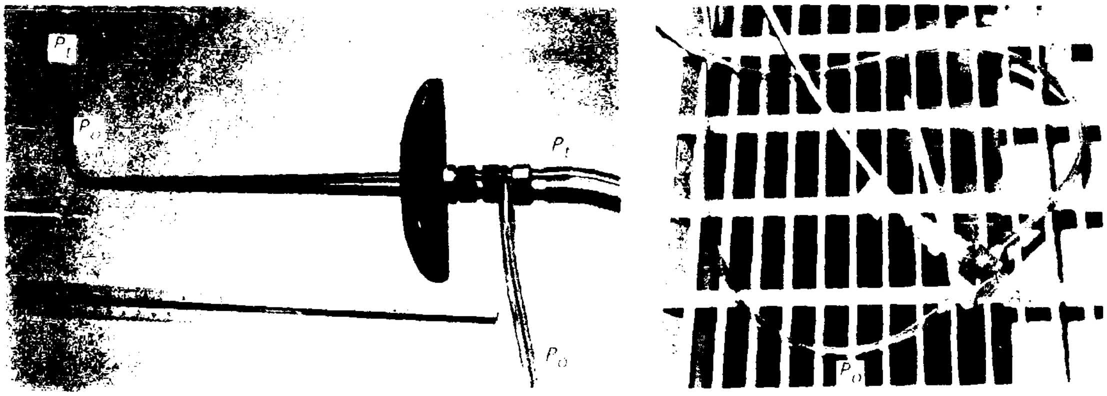
Piezometers

8. Six piezometer pairs were installed in the conduit during construction. Locations of the pairs are shown in Plate 1. The piezometer manifold is located in a well near the stilling basin. A 1.5-in. copper line connects the manifold to the reservoir for backflushing the piezometer lines. The backflush line and manifold locations are also shown in Plate 1. Figure 3 shows a typical piezometer being backflushed.

Pressure tranducers

9. Pitot tubes were installed in each air vent for measuring air demand. A 0.5-psid differential pressure transducer was used to measure the difference between the stagnation (total) pressure p_t occurring at the tip of the pitot tube and the static pressure p_o on the tube side. A pitot tube and differential pressure transducer with connecting tubing are shown in Figure 4. These points of measurement were designated AV1 and AV2 (Plate 1).

Figure 3. Conduit piezometer plate



a. Pitot tube

b. Differential pressure transducer

Figure 4. Air vent velocity instrumentation

10. A 50-psia pressure transducer was connected to the piezometer manifold for measuring the average pressure of each piezometer pair (designated PPP). A 50-psia pressure transducer was also used to measure pressure fluctuations downstream of the left control gate (PGR, Plate 1). This transducer was installed in the cover plate of the manhole location just downstream of the control gate. The transducer was housed in an adapter that was threaded into a hole drilled and tapped in the cover plate. The cover plate, transducer adapter, and electrical cord are shown in Figure 5.

Discharge measurements

11. Discharge measurements were made by the US Geological Survey (USGS), Water Resources Division, Austin, TX. The measurements were made from the upstream side of an I-35 bridge (Figure 6) located south of Belton, TX, and approximately 1.5 miles downstream of the project.

Other measurements

12. Other recorded data consisted of reservoir water-surface elevations, gate openings, air temperature, and water temperature at the intake level. These data were provided by project personnel and personnel of the US Army Engineer District, Fort Worth, Fort Worth, TX. Other atmospheric information was provided by the National Oceanic and Atmospheric Administration, from their Waco, TX, airport station.

Recording equipment

13. The recording equipment consisted of (a) model 01 strain gage

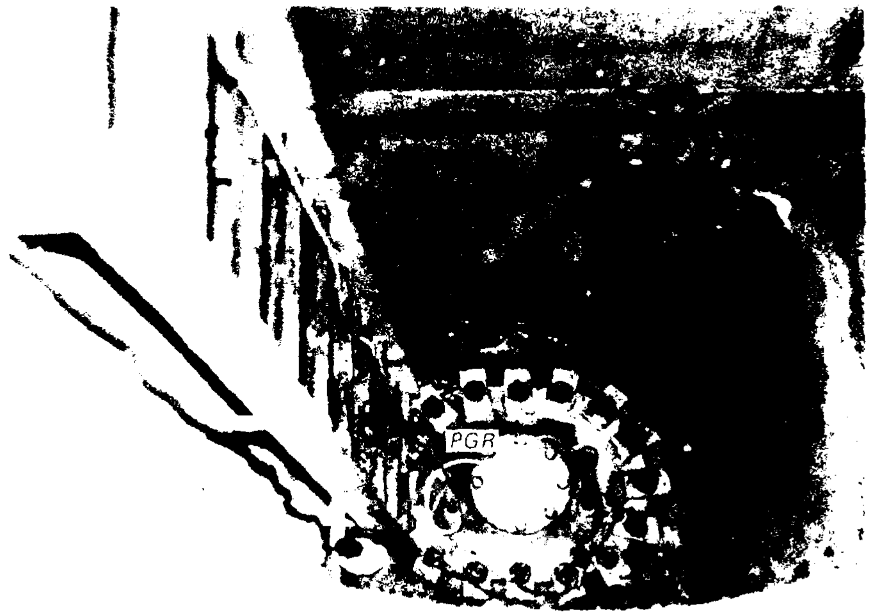


Figure 5. Cover plate and adapter for transducer (PGR)

Figure 6. USGS discharge measurements

bridge amplifiers fabricated at the US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, to condition the transducer output signal; (b) a Raycal model Store 14DS, 14-channel, frequency-modulated, magnetic tape recorder; and (c) a CEC model 5-134, 7-in. chart oscillograph capable of reproducing 18 channels of data.

Test Procedure

14. The tests were conducted on 30 June and 1 July 1987. All data were recorded on magnetic tape. During each individual test, a portion of the taped data was transferred to the oscillograph to confirm the data were being recorded and to make a visual check of the results. Voice comments on the tape and notes on the oscillograms were continuously made for later reference.

15. Procedure was the same for all five tests:

a. Record zero (no flow conditions), recorded at the beginning of the test program.

b. Record test number, date, etc.

c. Record step calibrations.

d. Raise gates to test opening. Allow flow to stabilize.

e. Record data on magnetic tape and oscillograms.

f. Measure discharge (USGS).

g. Record pool elevation, weather, and hydrological conditions (Fort Worth District).

PART III: TEST RESULTS AND ANALYSIS

16. All magnetic tape data channels were reduced simultaneously at WES, providing a direct time-dependent relationship among them. To reduce the data, a representative 1-min sample of each data channel was selected from each recorded 2-min test. The piezometer pair average pressures were recorded sequentially from the upstream to the downstream station during each test run. The other data station recordings were repeated with each piezometer pressure recording. The data were then digitally sampled to provide the following results and analysis.

Conduit Roughness

Plaster cast

17. The symbol k is used to represent the absolute roughness of a conduit wall. To determine this value at Stillhouse Hollow Dam (SHH), small 2- by 2-in. casts were first made of the wall. The surface of the samples was then mechanically mapped. From this a regression line (Figure 7) was mathematically determined, along with the standard deviation of the data points about the regression line s. Twice the value of s was used to represent the average physical absolute roughness of the wall cast, i.e., $k_{ave} = 2s$.

18. Twelve plaster casts were made at various locations in the SHH conduit just prior to the test period. Eleven of the casts were evaluated by recording eight traverses of each with an Ames dial gage. After k_{ave} was computed for each cast, the relative roughness was determined by dividing the

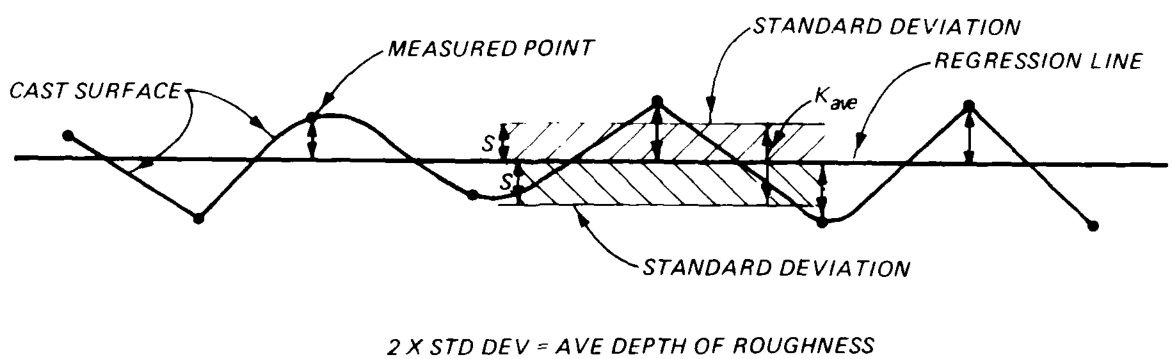


Figure 7. Definition of k_{ave}

conduit diameter D by this value: D/k_{ave} . A compilation of these values is given in Table 3.

19. The computed average physical relative roughness values were plotted versus the range of the test series Reynolds numbers and appear as the shaded area on the Moody diagram of Plate 2, Hydraulic Design Criteria Chart 224-1 (US Army Corps of Engineers (USACE)). Most of the data fall to the right of the Rouse rough pipe limit line (i.e., independent of Reynolds number) of the diagram. Therefore, the Von Karman-Prandtl equation for rough pipes was used to calculate the roughness coefficient f :

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \left(\frac{D}{2k_{ave}} \right) + 1.74 \qquad (1)$$

The computed roughness coefficients and their average values are also listed in Table 3. The combined average value is plotted in Plate 2 at the Reynolds number computed for Test 1 (for the reason given in paragraph 22).

Pipe aging

20. Colebrook (19˜9) proposed an expression for evaluating the effect of age upon pipe capacity. The equation reduces to the following, which can be used to predict changes in wall roughness with time:

$$k_2 = k_1 + \alpha T \qquad (2)$$

where

k_2 = last measured absolute roughness, in.

k_1 = initial measured absolute roughness, in.

α = rate of roughness growth, in./year

T = time between measurements, years

Limited casts were made by WES personnel in October 1983 (k_1). A list of these earlier k_{ave} values is also given in Table 3. Using these values and Equation 2, a rough estimate of α was calculated to be 0.001 in./year.

Conduit pressure

21. The Darcy-Weisbach equation is preferred for Corps use in computing energy losses in pressurized flow (Office, Chief of Engineers, US Army (OCE), 1980). The primary reason is because through use of the Moody diagram (Plate 2), the Reynolds number and the relative roughness properly account for

the differing friction losses in both the transitional and fully rough zones. The Darcy-Weisbach formula is expressed:

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \tag{3}$$

where

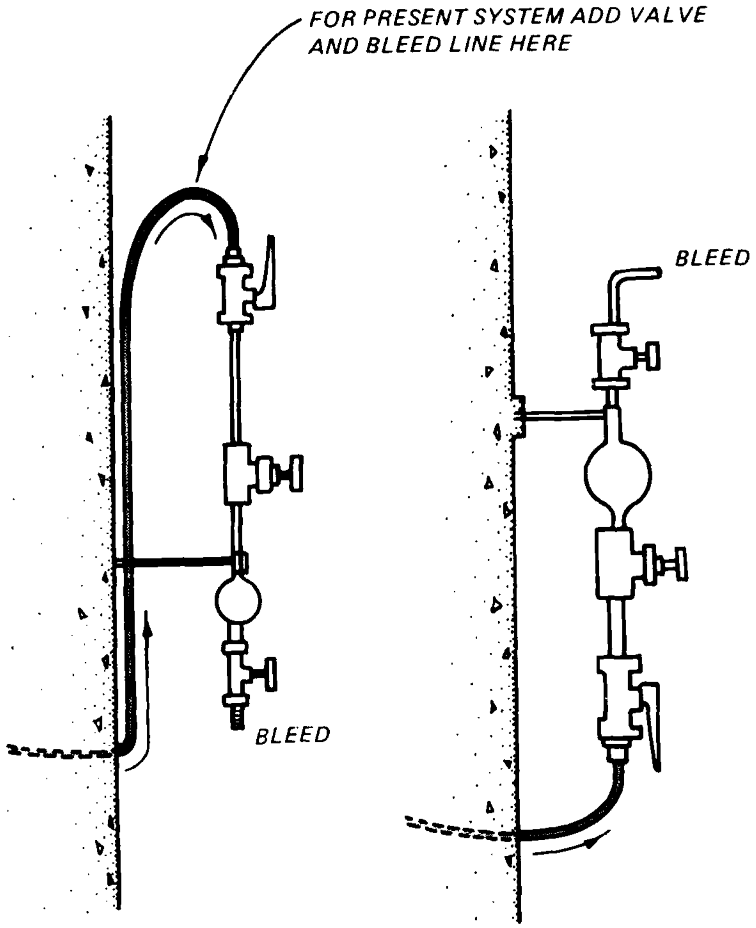
- h_f = head loss, or drop in piezometric pressure p, ft ($p/\gamma + z$ where γ is the specific weight of water, lb/ft^3, and z is the vertical distance from the datum to the conduit center line, ft)
- L = conduit length between measurement stations, ft
- v = average flow velocity, ft/sec
- g = acceleration of gravity, ft/sec^2

Pressures were measured along the conduit at the piezometer stations shown in Plate 1 to obtain the conduit piezometric gradient. From this the value of h_f was determined. All other terms were known except v, which was calculated using the continuity equation:

$$v = \frac{Q}{A} \tag{4}$$

where Q is the discharge in cubic feet per second and A is the conduit area in square feet. Equation 3 was then solved for the roughness coefficient f for comparison with the values obtained from the casts.

22. Considerable difficulty was experienced with the piezometer pressure system. Difficulty was experienced in recording a stationary pressure. In some cases, downstream pressures were greater than those upstream. The entire system was backflushed using the reservoir head, but the problem persisted. There may be some leaks in the system, although none were detected in the region of exposed tubing. The tubing from the piezometers enters the well above the manifold and bows upward. Air could be trapped in this inverted bow. It is recommended that future systems be designed so that piezometer tubing enters the well below the manifold (see Figure 8). Because of the problems, only the pressures from Test 1 were considered for use in the calculation of f. The head loss during Test 1 between piezometer pairs 3-4 and 11-12 with $L = 400.0$ ft (Plate 1) was 4.1 ft. Using these data and



a. Existing   b. Recommended

Figure 8. Piezometer manifold

Equation 3, f was calculated to be 0.0093. The ratio of this value to f_{ave} from the cast calculations is 0.0093/0.0110 = 0.85. Both are plotted for comparison in Plate 2 at a Reynolds number of 2.97×10^7.

23. The absolute roughness values shown in Table 3 varied over a rather wide range, having a standard deviation which was 40 percent of its average value. Correspondingly, the standard deviation of the roughness coefficients was only 7 percent of its average. This agrees with Rouse's (1971) statement: "Appreciable inaccuracies in the evaluation of k will not seriously affect the value of f ."

Air Demand

Point velocity

24. Pitot tube differential pressures were measured at the locations shown in Plate 1 (AV1 and AV2) for determining the air demand in the 32-in.-OD air vents. The pitot tubes and differential pressure transducers discussed in paragraph 9 were used for these measurements.

25. When a pitot tube is installed in a vent without flow, the static pressure p_o is exerted equally on all surfaces. With flow, a dynamic pressure $\rho v_p^2/2$ due to the point velocity v_p is added at the tube's leading edge. The total pressure p_t at the leading edge, then, is the sum of these pressures, and the pitot tube is sensitive only to velocity pressure changes since p_o occurs equally at all points. Therefore:

$$p_o + \frac{\rho v_p^2}{2} = p_t \quad \text{or} \quad v_p = \left(\frac{2\Delta p}{\rho}\right)^{1/2} \tag{5}$$

where

ρ = mass density, lb-sec^2/ft^4

Δp = differential pressure $(p_t - p_o)$, lb/ft^2

The point velocities were computed using Equation 5. The values, along with air temperature, mass density, and differential pressure, are given in Table 4.

Average velocity

26. Each pitot tube was located downstream of a straight length of vent. The equivalent upstream diameters D_e were 34.5 for AV1 and 42.2 for AV2. These lengths were assumed to be sufficient to ensure a fully developed turbulent flow at the pitot tubes. To obtain the average velocity of each vent v_a, Prandtl's one-seventh power law (Streeter 1966) was used to convert the point velocities to these values using the equation:

$$v_a = \left(\frac{98 v_p}{120}\right) \div \left(\frac{y}{r_o}\right)^{1/7} \tag{6}$$

where

y = radial distance from the vent wall to the pitot tube tip (10.375 in.)

r_o = vent inside radius (15.50 in.)

These values were computed and are listed in Table 4. They were then multiplied by the inner area of the vents to obtain the discharge (air demand) for each vent. Total air demand is also listed. The plot of individual vent air demand versus differential head is shown in Figure 9. The average total air demand versus gate opening is presented in Figure 10.

27. Field tests have shown (US Army Corps of Engineers (USACE)) that the largest quantities of air are required when the gate is about 5 percent open and again at some gate opening between 50 and 100 percent. The gate

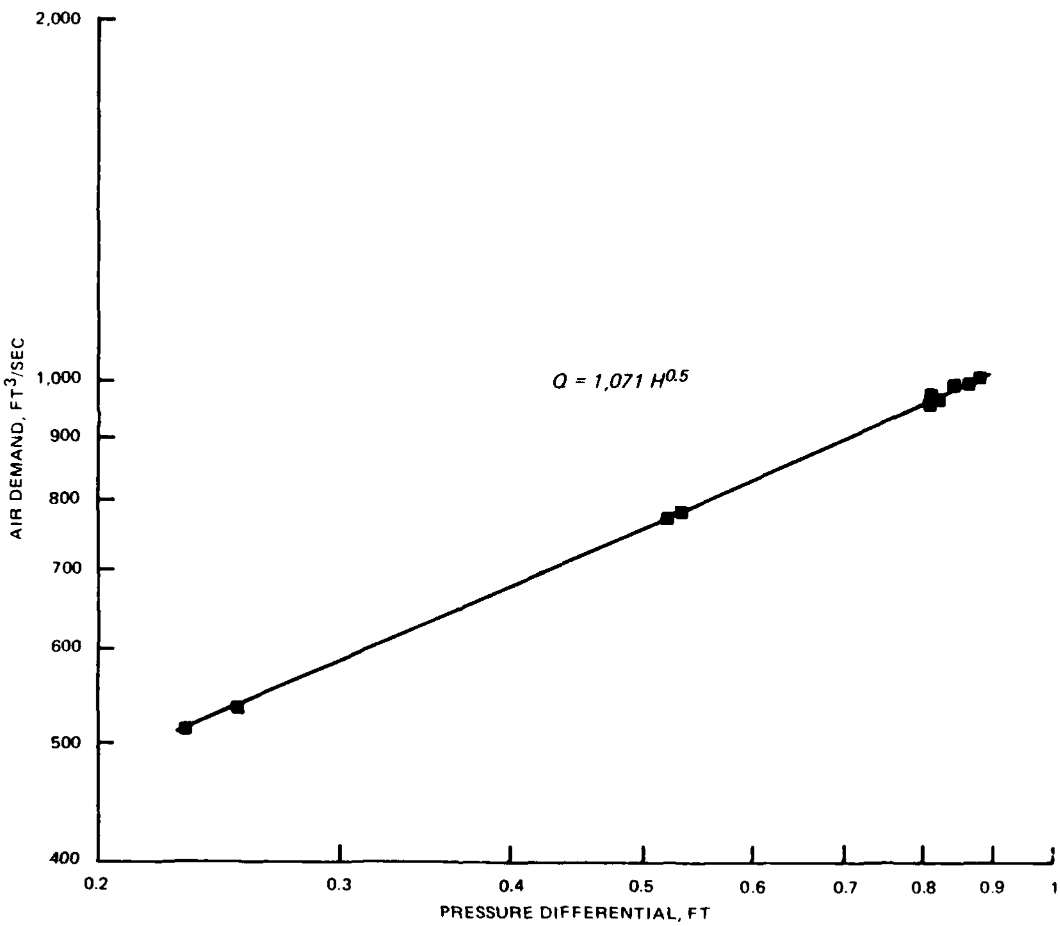


Figure 9. Individual vent air demand versus differential head

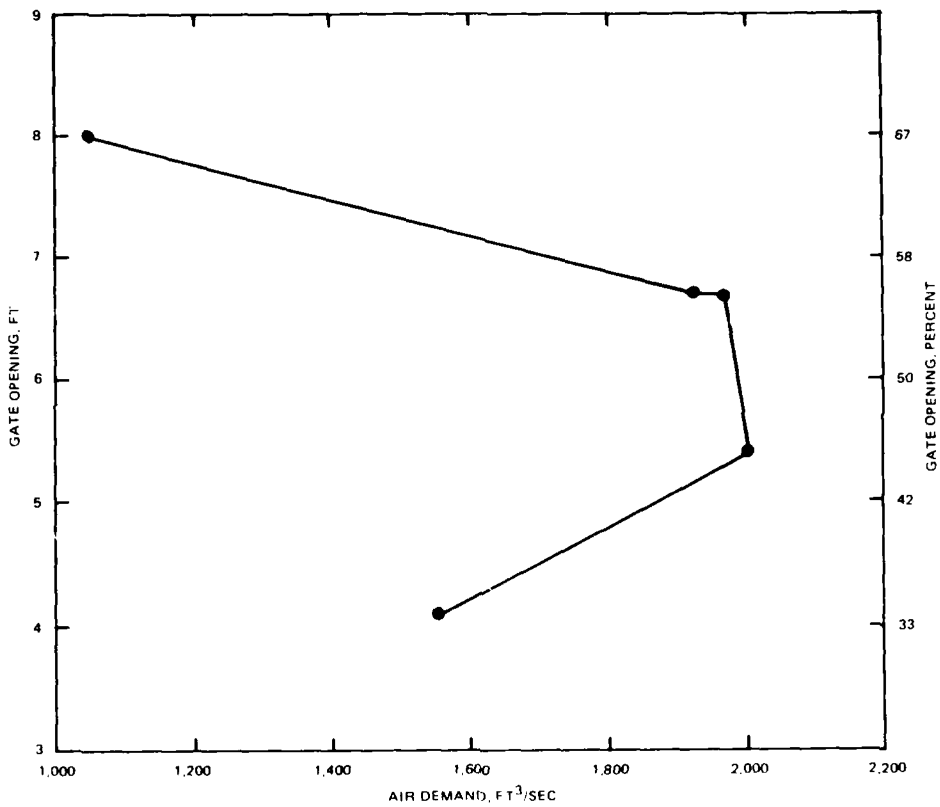


Figure 10. Average total air demand versus gate opening

openings tested at SHH were limited due to operational restrictions. At the openings tested, the maximum measured air demand occurred at openings of 5.4 ft and 6.7 ft as shown in Figure 10. It can be seen from the figure that the air flow probably peaks at some opening between 5 and 7 ft (or approximately 40-60 percent gate opening).

Cause of air demand

28. Generally, at high-head projects with large gate openings, a hydraulic jump is formed in the conduit. The air inflow from the vent at the top of the conduit is entrained by the turbulence of the jump and drawn downstream (Kalinske and Robertson 1943). Positive pressures were recorded at all times at all conduit piezometer pairs at SHH. For this reason it is assumed that a conduit-filling jump occurred during each test somewhere between the gate and the first piezometer pair. Dimensional analysis by Kalinske and Robertson (1943) leads to the following functional relationship:

$$\frac{Q_a}{Q_w} = \text{function } (F_1) \tag{7}$$

where

Q_a = air demand, ft^3/sec

Q_w = water discharge, ft^3/sec

F_1 = Froude number of the flow just upstream of jump

The air-water ratio was plotted versus $F_1 - 1$ since no hydraulic jump would occur when $F = 1$. From their data the functional relationship of Equation 7 was found to be:

$$\frac{Q_a}{Q_w} = 0.0066(F_1 - 1)^{1.4} \tag{8}$$

The air-water ratios and Froude numbers for the SHH data were determined and plotted in Plate 3, Hydraulic Design Criteria Chart 050-1 (USACE). In accordance with Hydraulic Design Criteria recommendations (USACE) the Froude number was based on the depth of the water at the gate vena contracta. The regression line equation of these SHH data is

$$\frac{Q_a}{Q_w} = 0.0087(F_1 - 1)^{1.9} \tag{9}$$

Most of the SHH data plot above the Corps-suggested design curve given in Plate 3. As shown in Table 4, the average velocities, in most cases, were greater than the Corps' recommended maximum air vent velocity of 150 ft/sec (OCE 1980). This may account for the higher Q_a/Q_w ratios of the SHH data.

29. The maximum recommended vent velocity of 150 ft/sec is specified by the Corps based on concern for high head losses in the vents resulting from high velocities. This could, in turn, result in subatmospheric pressures in the water conduit and possible accompanying cavitation damage. However, no damage was sighted at the time of the test program.

30. An instantaneous change in the pressure at the air vent-water conduit interface (location of transducer PGR) causes a corresponding, though time-delayed, velocity change in the air vent (location of AV1 and AV2). To estimate this time delay, a cross-correlation of the PGR and AV1 data was

made. A plot of the results is shown in Figure 11. The value of the time delay was calculated to be 0.275 sec.

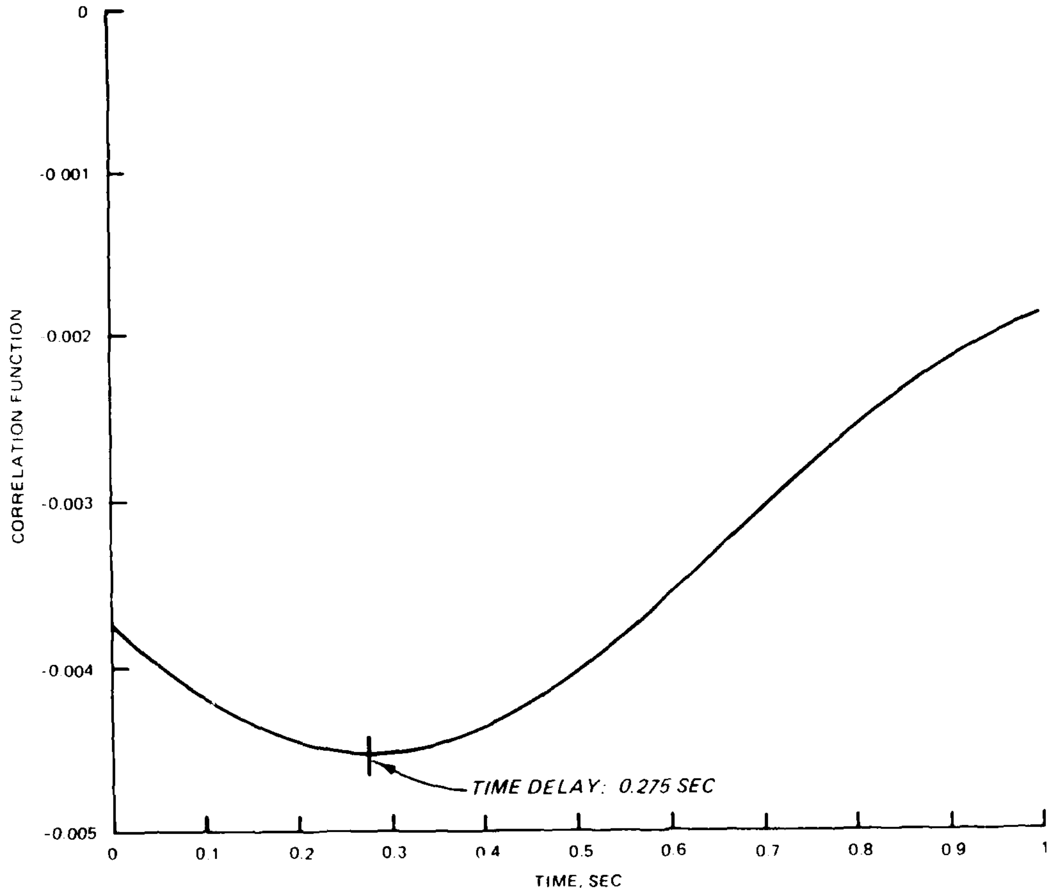


Figure 11. Cross-correlation of PGR and AV1 data

PART IV: CONCLUSIONS AND RECOMMENDATIONS

31. The following conclusions and recommendations are based on the analysis of the reduced SHH prototype data:

- a. The roughness coefficient f for the sluice is 0.0110 based on plaster casts made at the time of the test program. This differed from the value determined by head loss measurements by about 15 percent.
- b. The average rate of absolute roughness k_{ave} growth from 1983 to 1987 was approximately 0.001 in./year.
- c. In most tests the air vent velocity and head loss exceeded the limits suggested in Engineer Manual 1110-2-1602 (OCE 1980). However, no cavitation damage was detected in the sluice. Inspections are recommended periodically and following prolonged discharge periods.
- d. The ratios of air discharge through the vents and water discharge through the sluice were higher than the Corps' suggested values for a given Froude number. This agrees with the observation that the measured vent velocities are higher than the value used to compute the suggested Corps limit line shown in Plate 3.
- e. Based on available test data, air flow in the vents probably reached a maximum at a gate opening somewhere between 5 and 7 ft (40-60 percent).
- f. Piezometer manifolds should be designed to minimize the possibility of trapped air in the system.
- g. Data from this report should be added to Hydraulic Design Criteria Chart 050-1 (USACE) as shown in Plate 3.

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Table 1

Summary of Test Conditions

Test No.	Gate* Opening ft	Pool El	Water Discharge ft^3/sec	Average Conduit Velocity ft/sec	Reynolds No.** 10^7	Date 1987	Test Time Start	Test Time Stop
1	4.1	638.22	3,312	29.3	2.97	6/30	1151	1221
2	5.4	638.17	4,260	37.7	3.83	6/30	1336	1358
3	6.7	638.00	5,410	47.8	4.86	6/30	1834	1915
4	6.7	637.32	5,410	47.8	4.86	7/01	0939	1017
5	8.0	637.25	6,250	55.3	5.62	7/01	1110	1155

* Both gates open to same elevation.
** Water temperature 62.4° F.

Table 2

Instrumentation

Code*	Instrument Type	Instrument Range	Location Sta	Location El	Function
PGR	CEC 4-312	50 psia	16+10	527.0	Pressure downstream of gate
PPP	CEC 4-312	50 psia	24+85	513.0	Average pressure of each piezometer pair
AV1	Validyne DP 15-20	0.5 psid	16+05	604.0	Air vent velocity
AV2	Validyne DP 15-22	0.5 psid	16+05	584.0	Air vent velocity

* See Plate 1.

Table 3

Conduit Wall Roughness Data

Date of Cast	Cast No.	Conduit Sta*	Peripheral Location**	Absolute Roughness k_{ave}, in.	Relative Roughness D/k_{ave}	Roughness Coefficient f
6/87	2	19+00	M	0.00711	20,262	0.0105
6/87	3	19+00	L	0.01101	13,076	0.0114
6/87	4	20+00	M	0.00556	25,881	0.0101
6/87	5	23+00	M	0.00794	18,140	0.0107
6/87	7	22+00	M	0.01573	9,153	0.0122
6/87	8	22+00	L	0.00674	21,378	0.0104
6/87	9	24+00	M	0.00898	16,027	0.0110
6/87	22	20+00	L	0.00925	15,567	0.0110
6/87	23	20+00	L	0.01806	7,976	0.0125
6/87	44	21+00	M	0.00936	15,383	0.0110
6/87	88	21+00	L	0.00756	19,044	0.0106
			Average	0.00975	16,535	0.0110
			Standard deviation	0.00386	5,252	0.0008
			Percent of average	40	32	7
10/83	1	19+00	M	0.00479	30,056	0.0098
10/83	2	19+00	L	0.00735	19,596	0.0105
			Average	0.00607	24,826	0.0101

NOTE: Roughness coefficient from piezometer pressures: $f_{pp} = 0.0093$.

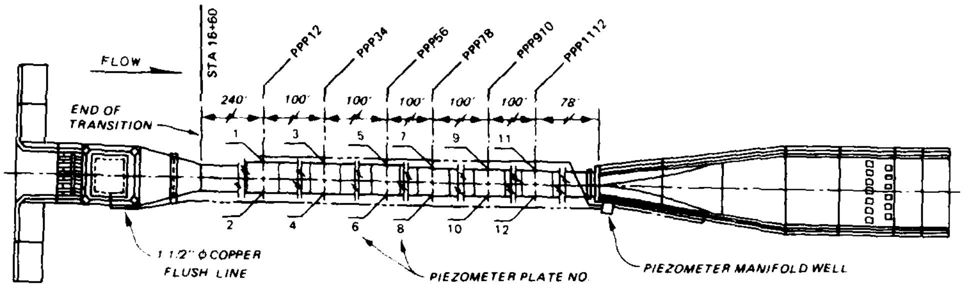
* See Plate 1.

** M = conduit midheight, L = conduit lower one-third.

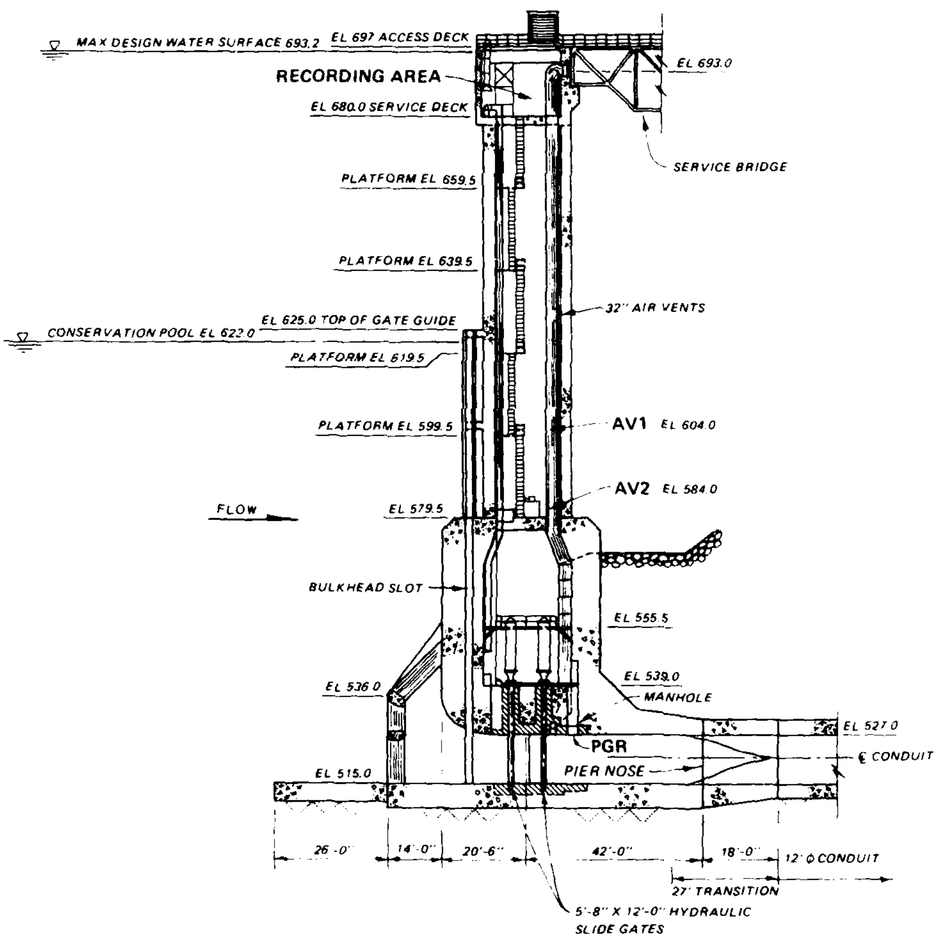
Table 4

Air Demand Data

Test No.	Air Temp °F	Mass Density 10^{-4} lb-sec^2/ft^4	AV1 Pitot Differential Pressure lb/ft^2	AV1 Average Point Velocity v_p ft/sec	AV2 Pitot Differential Pressure lb/ft^2	AV2 Average Point Velocity v_p ft/sec	AV1 Average Vent Velocity v_a ft/sec	AV2 Average Vent Velocity v_a ft/sec	AV1 Discharge ft^3/sec	AV2 Discharge ft^3/sec	Total Discharge ft^3/sec
1	90	22.4	33.55	173.08	32.69	170.84	149.57	147.63	784	774	1,558
2	90	22.4	55.44	222.49	54.43	220.45	192.27	190.51	1,008	999	2,007
3	100	22.0	53.14	219.78	51.12	215.58	189.93	186.29	996	976	1,972
4	82	22.7	50.98	211.93	51.84	213.71	183.14	184.69	960	968	1,928
5	88	22.5	14.40	113.70	15.84	118.13	98.26	102.54	515	537	1,052



PIEZOMETER PLATES & MANIFOLD



INTAKE TOWER

STILLHOUSE HOLLOW DAM
INSTRUMENTATION LOCATIONS

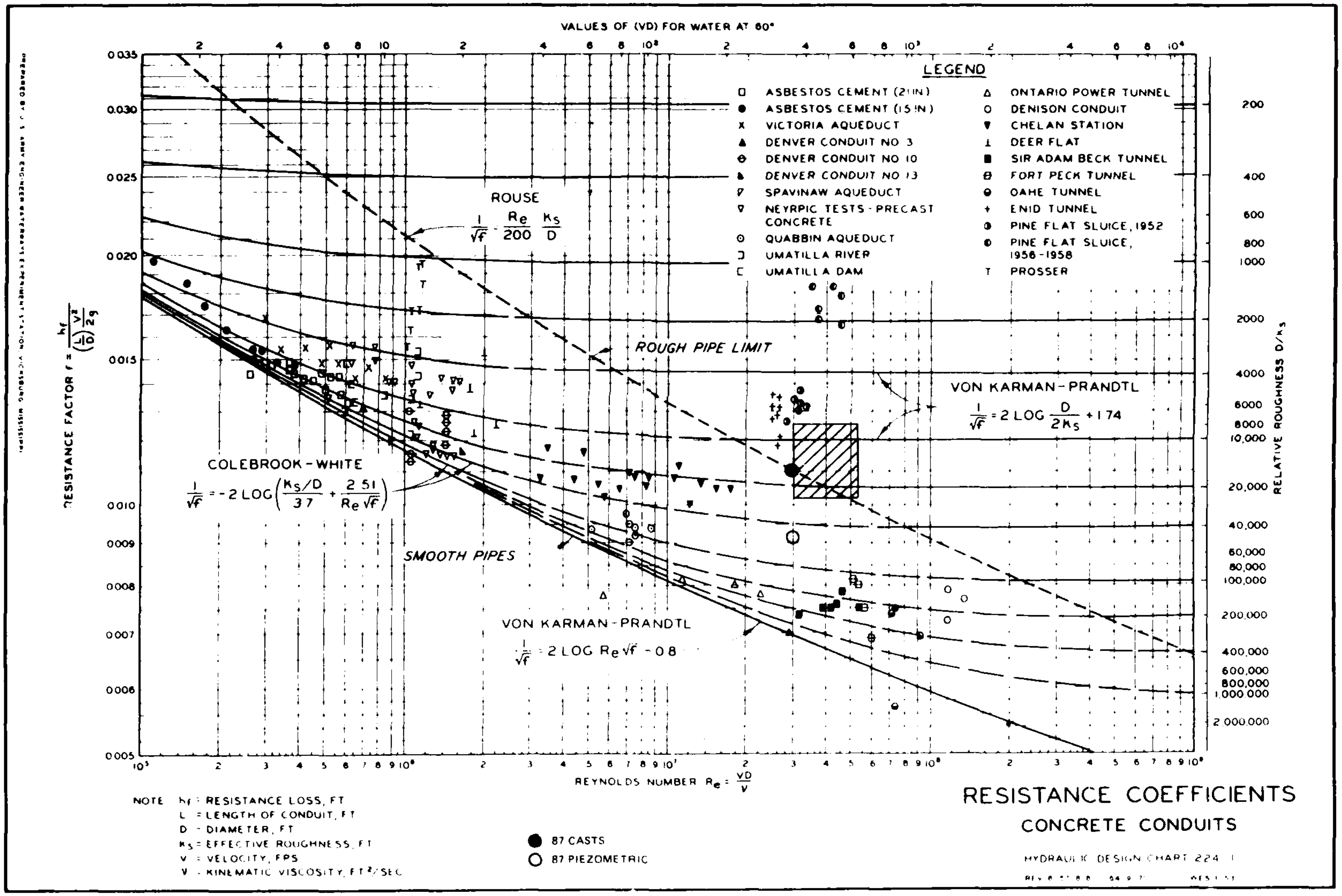
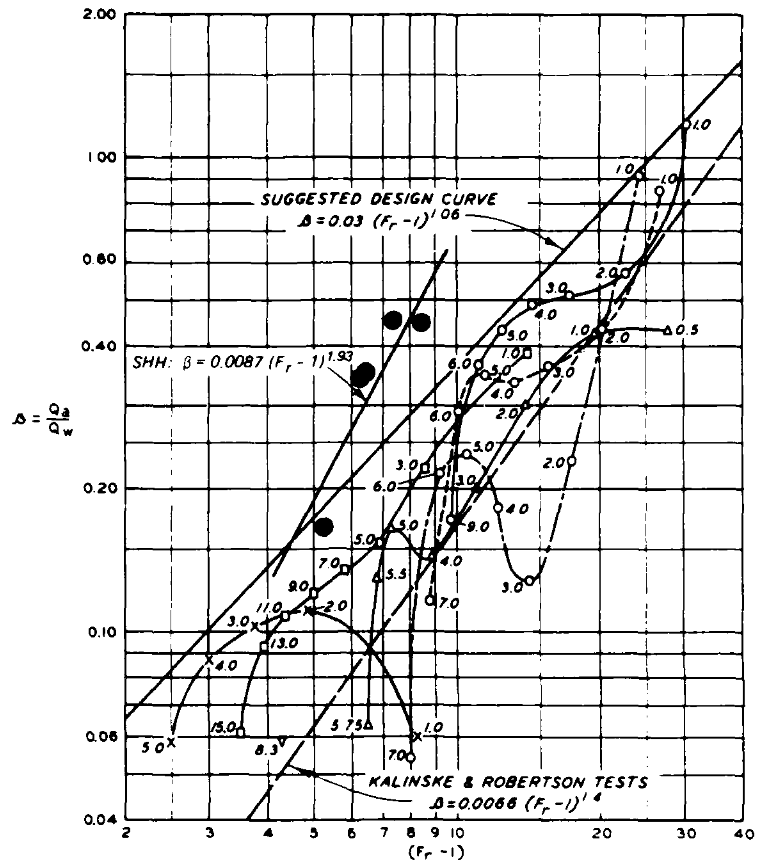

VALUES OF (VD) FOR WATER AT 60°
LEGEND
ASBESTOS CEMENT (2¼ IN)
ASBESTOS CEMENT (15 IN)
VICTORIA AQUEDUCT
DENVER CONDUIT NO 3
DENVER CONDUIT NO 10
DENVER CONDUIT NO 13
SPAVINAW AQUEDUCT
NEYRPIC TESTS - PRECAST CONCRETE
QUABBIN AQUEDUCT
UMATILLA RIVER
UMATILLA DAM
ONTARIO POWER TUNNEL
DENISON CONDUIT
CHELAN STATION
DEER FLAT
SIR ADAM BECK TUNNEL
FORT PECK TUNNEL
OAHE TUNNEL
ENID TUNNEL
PINE FLAT SLUICE, 1952
PINE FLAT SLUICE, 1956-1958
PROSSER
ROUSE
$\frac{1}{\sqrt{f}} = \frac{R_e}{200} \frac{K_s}{D}$
ROUGH PIPE LIMIT
VON KARMAN - PRANDTL
$\frac{1}{\sqrt{f}} = 2 \text{ LOG } \frac{D}{2K_s} + 1.74$
COLEBROOK - WHITE
$\frac{1}{\sqrt{f}} = -2 \text{ LOG} \left(\frac{K_s/D}{3.7} + \frac{2.51}{R_e \sqrt{f}} \right)$
SMOOTH PIPES
VON KARMAN - PRANDTL
$\frac{1}{\sqrt{f}} = 2 \text{ LOG } R_e \sqrt{f} - 0.8$
RESISTANCE FACTOR $f = \frac{h_f}{\left(\frac{L}{D}\right) \frac{V^2}{2g}}$
RELATIVE ROUGHNESS D/K_s
REYNOLDS NUMBER $R_e = \frac{VD}{\nu}$
NOTE h_f = RESISTANCE LOSS, FT
L = LENGTH OF CONDUIT, FT
D = DIAMETER, FT
K_s = EFFECTIVE ROUGHNESS, FT
V = VELOCITY, FPS
ν = KINEMATIC VISCOSITY, FT²/SEC
87 CASTS
87 PIEZOMETRIC
PREPARED BY U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI
RESISTANCE COEFFICIENTS
CONCRETE CONDUITS
HYDRAULIC DESIGN CHART 224-1

PLATE 2



NOTE. $F_r = V/\sqrt{gy}$ (FROUDE NUMBER)

V = WATER VELOCITY AT VENA CONTRACTA, FT/SEC

y = WATER DEPTH AT VENA CONTRACTA, FT

Q_a = AIR DEMAND, CFS

Q_w = WATER DISCHARGE, CFS

● DATA DERIVED FROM STILLHOUSE HOLLOW DAM FIELD TESTS, 1987

LEGEND

O———O PINE FLAT - H = 370 FT
O- - - - -O PINE FLAT - H = 304 FT
O— — —O PINE FLAT - H = 254 FT
□———□ DENISON - H = 84 FT
X———X HULAH - H = 24 FT
Δ———Δ NORFORK - H = 154 FT
∇ TYGART - H = 92 FT

H = HEAD, POOL TO CONDUIT CENTER LINE

FIGURES ON GRAPH SHOW GATE OPENING IN FEET.

AIR DEMAND

REGULATED OUTLET WORKS

HYDRAULIC DESIGN CHART 050-1

REV 1-64 WES 4-1-52